

Challenges of laser spectrum metrology in 248 and 193-nm lithography

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ABSTRACT

Several approaches for high-resolution laser metrology have been discussed. One approach is to use a multiple-etalon spectrometer, which has two or more etalons with different FSRs. This approach can increase both the resolution at FWHM and the tails, as well as increase the spectrum range of the instrument. With the proper alignment, this multiple etalon configuration can produce an instrument whose resolution is equal to or better than the highest resolution etalon while still maintaining the FSR of the lower resolution etalon. In the configuration tested, a spectrometer designed for 248nm was constructed with a 2pm etalon and a 20pm etalon. The resolution of this multi-pass, multi-etalon (MPME) spectrometer produced an instrument function of 0.086pm FWHM and 0.339pm for the integrated 95% level over an integration range of 20pm. Another approach is to use a combination of diffraction grating and etalon - based spectrometers. In this approach, the etalon provides high resolution for FWHM measurements, while diffraction grating provides accurate measurement of the spectrum tails over the wide scanning range. This idea has been tested with a 193 nm instrument.

Keywords: excimer laser, metrology, spectrum measurements

1. INTRODUCTION

As lithographers continue to push the resolution down to 0.15 μm and below, the importance of precision laser spectrum line control becomes ever more important. This is especially true for 193nm, in part due to higher dispersion of fused silica and CaF_2 at 193 nm, and in part due to the push by the lens designers towards higher NA lenses¹. In order to achieve more accurate control over the laser spectrum, improved metrology is required. This metrology should provide high-resolution measurements of the spectrum width (FWHM – level measurements) as well as accurately characterizing the spectrum in the “tails”². Line shape can be defined either by the widely used I95% definition (the spectrum range containing 95% of the laser energy) or can be characterized by a lens image quality loss due to chromatic aberrations. In order to accurately define the laser shape, the metrology tool must have a working spectral range large enough to completely cover the laser spectrum. Ideally, this spectrum range should be about 25 - 50X the laser FWHM width. Currently, the high-resolution grating spectrometers are commonly used for this task^{3,4}. Unfortunately, there seems to be a practical limit on the resolution of these instruments, which is about 0.1pm at FWHM level and beyond which the operating cost and complexity of the device goes up exponentially.

On the other hand, the new generation of ultra-line-narrowed excimer lasers will require metrology with twice the resolution of current designs. To improve the resolution of a spectrometer, a Fabry-Perot etalon may be used as the dispersive element rather than a diffraction grating. Etalons are routinely capable of producing resolving powers on the order of 10^7 . Because etalons do not require the use of a slit aperture, their luminosity is high. Unfortunately, to achieve high resolving powers with an etalon spectrometer one would traditionally have to sacrifice free spectral range.

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The free spectral range (FSR) of a Fabry-Perot etalon is defined as the maximum bandwidth that can be measured without aliasing. The ratio of the FSR of an etalon to its minimum resolvable bandwidth is its finesse. Therefore, to increase resolution while keeping the FSR constant the finesse must be increased. Due to practical limitations, the finesse of a plano, Fabry-Perot etalon is typically constrained to values less than 100. In the case of the DUV spectrum the finesse is usually further constrained to values less than 50.

The transmission of an etalon when illuminated by a diffuse monochromatic source is maximized at specific angles. These fringes of equal inclination produce a concentric ring pattern when imaged by a lens. The angular separation between consecutive fringes of an etalon defines the FSR of the etalon in angle space. The relationship between the maximum transmission angle, θ , of an etalon with respect to wavelength is defined by:

$$m\lambda = 2nd \cos(\theta) \quad (1)$$

where :

m = fringe order

n = index of refraction

d = plate separation of etalon

These multiple fringes or pass bands in the transmission of a single etalon limit its usefulness to a region between consecutive fringes. If one were able to suppress some of the fringes, the FSR of an etalon could be increased. This can be accomplished by adding a second etalon whose plate separation is different from the primary etalon.

From (1) it can be seen that if the spacer distance from two different etalons were matched to an integer multiple, k , the transmissions of the two etalons would match at orders m and (m/k) , see (2). The pass bands of the two etalons when matched at a single wavelength are matched for all wavelengths within the FSR etalon.

$$\begin{aligned} \frac{m\lambda}{2nd} &= \cos \theta & \frac{m_1\lambda}{2n_1d_1} &= \cos \theta \\ nd &= kn_1d_1 \\ \frac{(m/k)\lambda}{2n_1d_1} &= \frac{m_1\lambda}{2n_1d_1} \end{aligned} \quad (2)$$

There is a complication when using secondary etalons to suppress etalon pass bands. The problem arises from the practical limitations of the etalon pass bands. A true etalon pass band has a finite width and a non-zero amount of bleed through between consecutive fringes.(Figure 1) These non-ideal characteristics of true etalon transmission functions produce subsidiary transmission peaks between designed pass bands (see Figure 2).

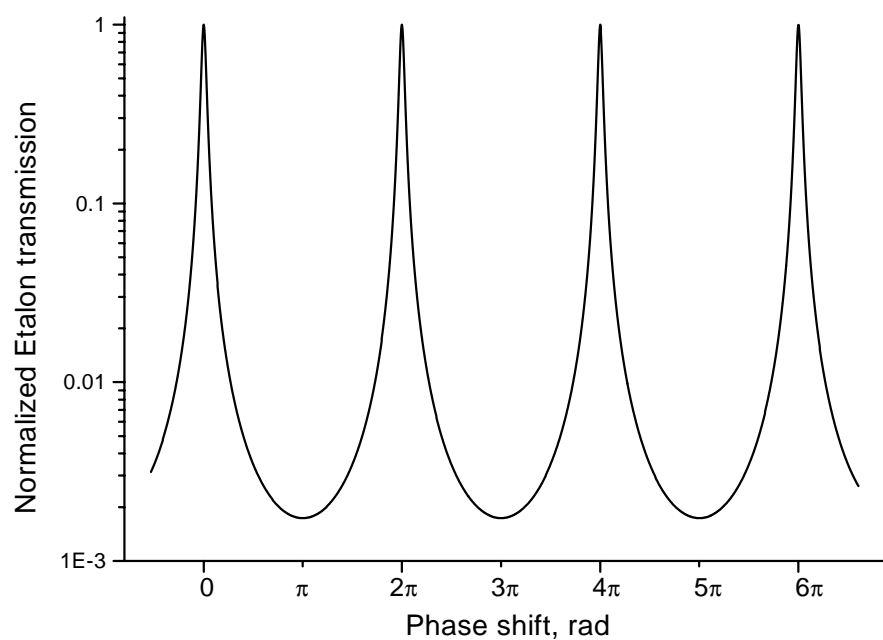


Figure 1. Transmission peaks of an etalon with 92% mirror reflectivity.

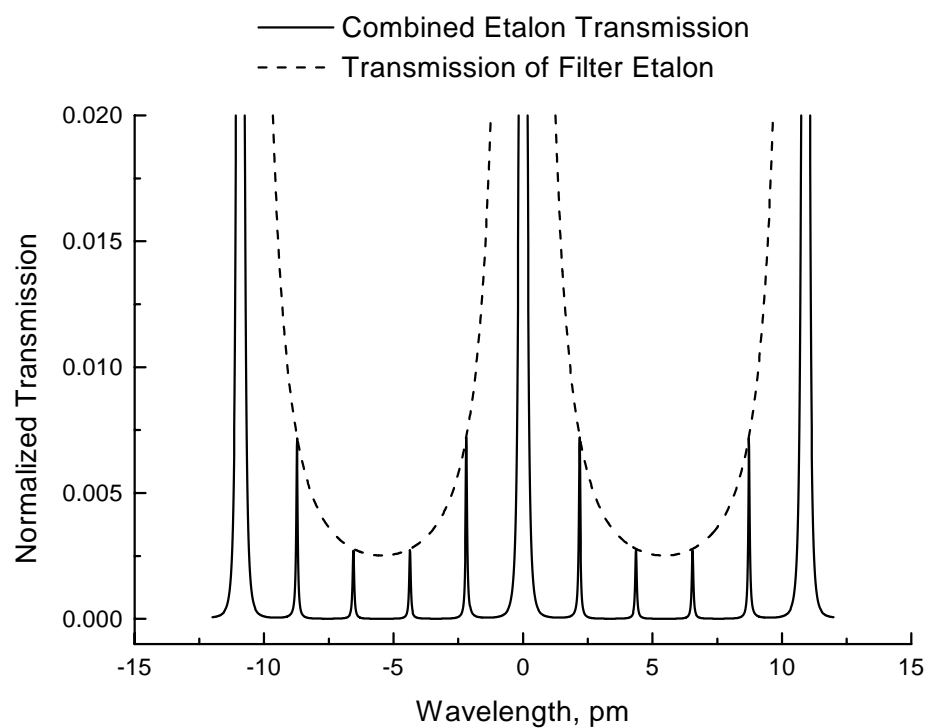


Figure 2. Combined transmission of two etalons with different FSR values (FSR ratio is 5).

After review of Figure 2, one can see that the maximum amplitude of the subsidiary peaks is less than 1%. Although this number is quite small and would be acceptable for most applications, it significantly increases the value of the integrated 95% slit function. Figure 3 shows the effect of subsidiary peaks on the integrated energy of a theoretical transmission function of the combination of a 20pm and a 2pm etalon. The amplitude of the peaks is large enough to be discernible from the baseline without magnification and their influence produce the step like features in the integrated energy curve.

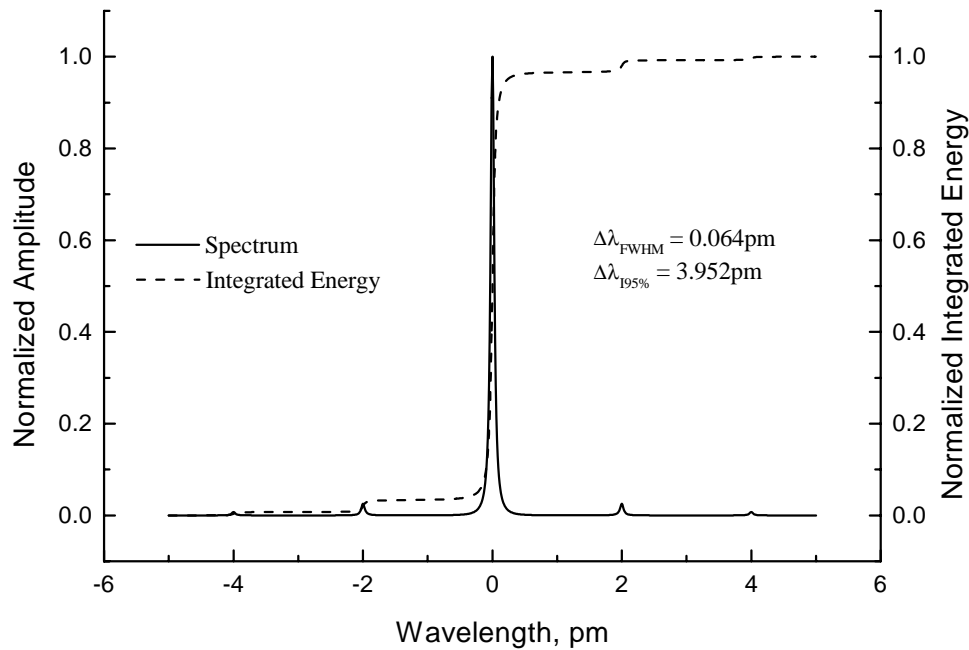


Figure 3. Theoretical transmission function of the combination of 20pm and 2pm FSR etalons.

One way to reduce the amplitude of the subsidiary peaks would be to propagate through the secondary filter etalon twice. The effect of “double passing” the filter etalon would square its transmission function. The transmission function of this etalon would then have slightly narrower primary pass bands and a significantly lower bleed-through level between pass bands². Lowering the bleed-through level of the filter etalon has a direct effect on the amplitude of the subsidiary peaks. Modeling the combined transmission function of two etalons each with a finesse of 30 and an etalon gap ratio of 10 shows that the maximum subsidiary peak is 0.0257. Therefore, the maximum subsidiary peak of the combined etalons after “double passing” the filter etalon $(0.0257)^2 = 0.00066$. Figure 4 shows the theoretical transmission function and the integrated energy of the combination of a 20pm etalon and a 2pm etalon where the 20pm etalon is operated in double pass mode. Note that the FWHM of the transmission function did not change but the integrated 95% width decreased by almost 20 fold.

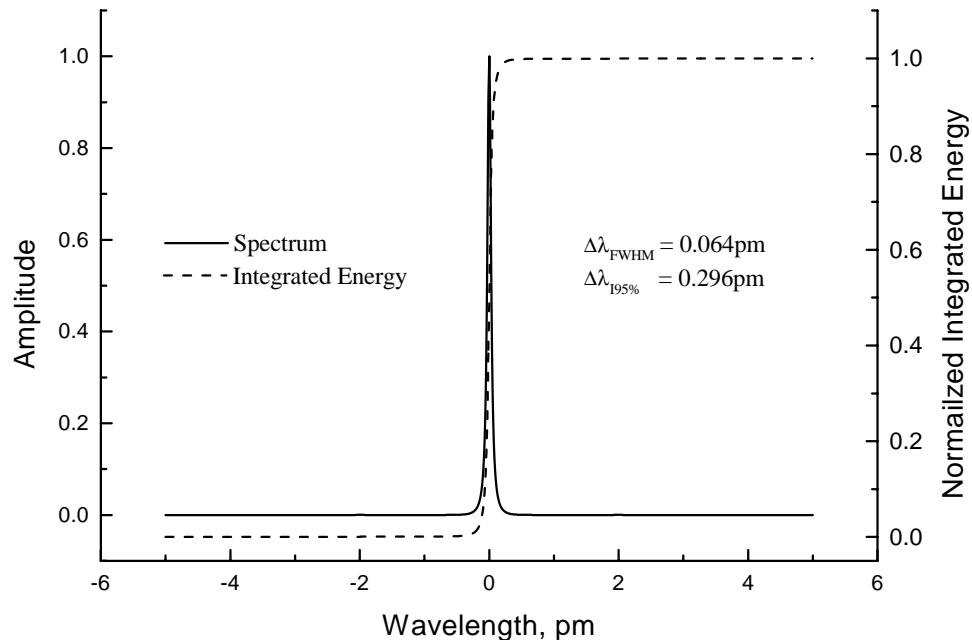


Figure 4. Theoretical slit function of double-pass 20 pm etalon and a single pass 2 pm etalon

2. MPME SPECTROMETER TESTING AND RESULTS

An etalon spectrometer was constructed using a 20pm and a 2pm etalon (see Figure 5). The 20pm etalon was used in a double pass configuration to suppress unwanted pass bands of a 2pm etalon. The layout of the spectrometer has the light first enter a reducing telescope. The telescope produces a reduction factor of 3. The telescope is required to image the entire input beam on a small diffractive diffuser. After the beam is diffused, it is spatially filtered to remove any zero order components, which could distort the spectrum. The beam is then focused onto the 20pm filter etalon. The focusing of the beam reduces the aperture and therefore improves the flatness finesse of the filter etalon. After propagating through the etalon, the beam is laterally displaced and retro-reflected by a hollow corner cube. The lateral displacement enables a pick-off mirror to redirect the beam after it propagates through the 20pm etalon a second time. Finally, the beam is directed through the primary 2pm etalon and then imaged by 1.5 meter lens onto a linear photo-diode array. The entire spectrometer fits on a 2 x 1 foot optical breadboard.

To align the transmission functions of the two etalons relative to each other required tuning one of them. The 2pm etalon was an air spaced etalon and was pressure tuned to match the 20pm etalon. The pressure tuning was accomplished by enclosing the etalon in a sealed housing and connecting it to an adjustable bellows by a flexible tubing. By compressing the bellows the gas pressure and therefore the FSR of the etalon could be adjusted.

Testing of the impulse response of the MPME spectrometer was conducted by using a frequency doubled argon laser as a monochromatic source. A 1024 element, linear photo-diode array (PDA) and a digitizing oscilloscope recorded the fringe pattern produced by the spectrometer. In addition to the fringe image, a dark level image was recorded. Each of the two files represented the average of 60 frames of the PDA running at a line rate of about 90 hz. The integration time of each frame was approximately 10.5 ms. The recorded images were processed by subtracting the dark level image from the fringe image and fitting a base line to the resulting data. The resulting data was then graphed in Figure 6.

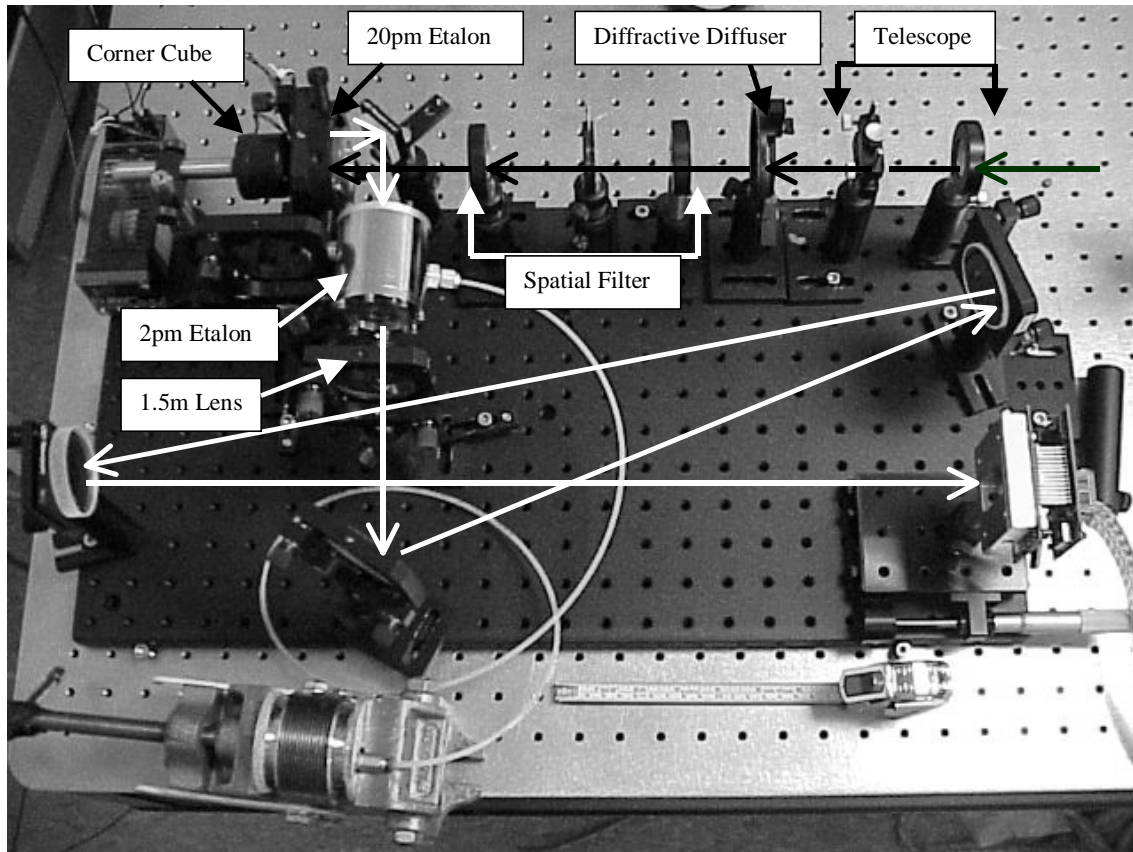


Figure 5. The Multi-pass, Multi-etalon Spectrometer.

The experimental transmission function recorded matches closely with the modeled function for the MPME spectrometer. The slightly inferior FWHM performance of the spectrometer over the modeled value was most likely due to inadequate detector resolution. The 25 micron size pixels were comparatively large to the width of the fringe pattern produced. To reduce this problem, the size of the fringe pattern was magnified by using a longer 1.5 meter focal length lens. At this magnification the diameter of the first fringe when positioned 10pm from the center is too large to be imaged by the detector. Even at this maximum magnification the FWHM of the fringe is 3 pixels or less. Therefore to utilize the full resolution of this spectrometer design would require a linear array with at least 2048 pixels.

The preferred embodiment of the spectrometer would have both etalons to be of the air spaced type and to have the tuning accomplished by pressure tuning the 20pm etalon. By tuning the 20pm etalon, the variability of the position of the first fringe would also be reduced. Since the FSR of an etalon bounds the position of a fringe with regards to wavelength, tuning the 20pm etalon would set the variability to 2pm. With lower fringe position variability, a more consistent integration range for calculating the integrated 95% width can be maintained for all wavelengths.

The practical limitations of this type of design sets the maximum ratio between etalon gaps at about 10. When the gap ratio of two etalons exceed 10, the proximity of the first subsidiary peak to the designed pass band causes a substantial increase in the integrated 95% width. Using this gap ratio guideline and the additional constraint of a minimum FSR of 10pm, sets the highest resolution MPME spectrometer to a device using a 10pm etalon and 1pm etalon. The theoretical transmission function of such a device with an estimated finesse value of 30 for both etalons produces a FWHM of 0.03pm and an integrated 95% of 0.15pm.

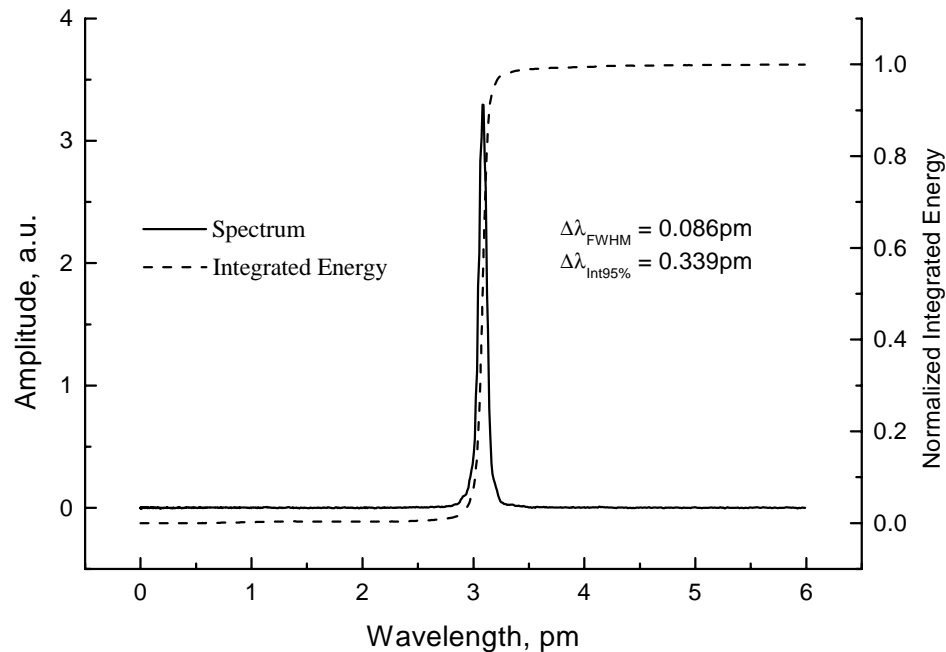


Figure 6. The experimental slit function of the MPME Spectrometer measured with a frequency-doubled Ar-ion laser at 248.25nm. The MPME spectrometer consists of a double-pass 20pm etalon and a single pass 2pm etalon.

3. HIGH-RESOLUTION ETALON-GRATING MONOCHROMATOR

Another concept to increase the resolution of spectral measurements is to combine the dispersion power of a grating and an etalon. Figure 7 shows a setup realizing this idea. A laser beam is focused by the lens, *L1* onto the diffuser, *D*. This diffuser could be a ground, fused silica diffuser or a holographic diffuser. The diffuser scatters the light before it enters the etalon, *ET*. This etalon determines the FWHM resolution of the instrument and it should have the highest practical finesse. We used an etalon with a finesse of about 30 and FSR of 1.5 pm. The light, after passing through the etalon, is collected onto the slit, *S1*, by the lens, *L2*, which has a focus length of 50cm. A 5x200 μm slit was used. The etalon is aligned so that the slit, *S1*, is in the exact center of the fringe pattern created by the etalon. This slit is the entrance slit of the grating spectrometer. The light is collimated by the lens, *L3*, and illuminates the 250mm echelle grating, *GR1*, which works in Littrow mode. A small deviation from Littrow enables the pick-up mirror, *M1*, to separate the diffracted beam and direct it onto the exit slit, *S2*, where the signal is measured with a photo-multiplier tube, *PMT*. A partially transmitting mirror, *M2*, provides for the double pass on the grating in order to increase the dispersion⁴. The light, reflected from *GR1* for the first time, is then reflected by *M2* back to the grating for the second pass. The second reflection from *GR1*, which passed through *M2* is picked up by the mirror, *M1*. This scheme allows the doubling of the grating dispersion with relative ease but at the cost of reduced efficiency. Efficiency, however, is usually not a problem.

With this scheme, the etalon and grating have to be tuned relative to each other and remained fixed during the scan. The scan is accomplished by scanning the wavelength of the laser. The exact wavelength can be controlled with the laser's internal wavemeter. Tuning of the grating spectrometer can be accomplished by either rotating the grating or moving the slit, *S2*. Tuning the air gap of the etalon can be accomplished as described in MPME spectrometer using an adjustable bellows. The method used in the experiment was to tune the grating to the etalon and then scan the laser through the coincident pass band.

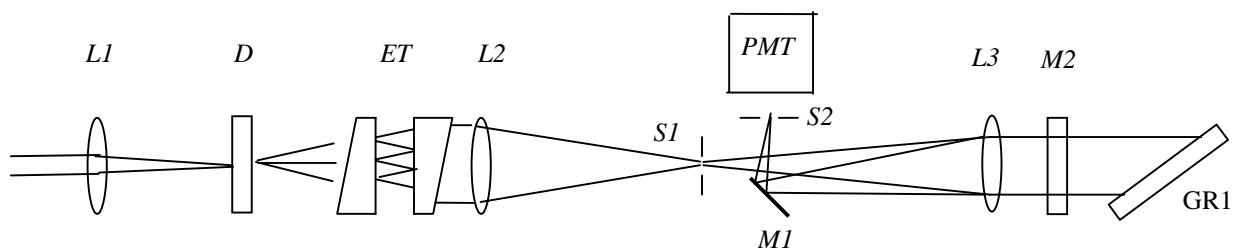


Figure 7. High-resolution etalon-grating monochromator.

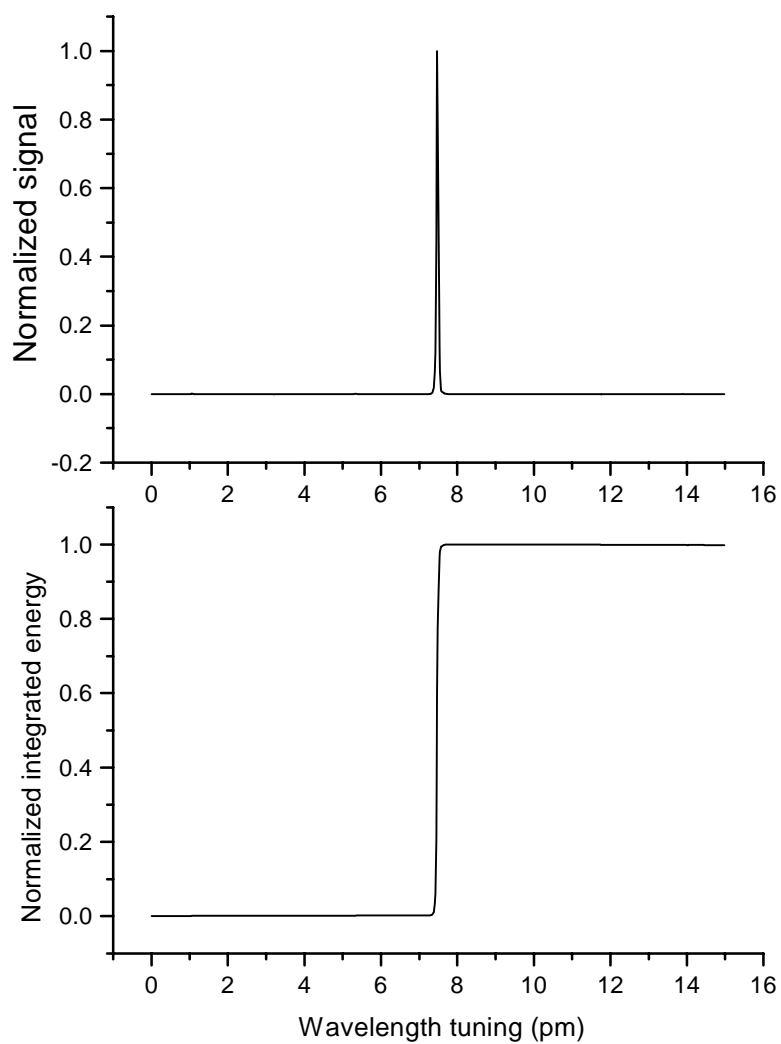


Figure 8. Calculated slit function of the etalon-grating monochromator with 1.5 pm high-finesse etalon and double-pass echelle grating spectrometer.

Figure 8 shows the calculated slit function of this monochromator. $\Delta\lambda_{\text{FWHM}}$ of the slit function is 0.034pm and $\Delta\lambda_{195\%} = 0.091\text{pm}$. This is a big improvement compared to $\Delta\lambda_{\text{FWHM}} = 0.11\text{pm}$ and $\Delta\lambda_{195\%} = 0.5\text{pm}$ for the double pass grating spectrometer alone⁴.

Figure 9 shows the spectra of an ArF excimer laser measured with this new monochromator and with a double pass grating spectrometer. The measurements were done at different times, so the actual bandwidth of the laser might have been slightly different in these two cases. The shape of the spectrum, and in particular the ratio of $\Delta\lambda_{\text{FWHM}} / \Delta\lambda_{195\%}$ is quite consistent for the laser, however. The $\Delta\lambda_{\text{FWHM}}$ value for the monochromator is 0.54pm as compared to 0.51pm for the grating spectrometer. On the other hand, the $\Delta\lambda_{195\%}$ value for the monochromator is 1.03pm as compared to 1.24pm for the grating spectrometer. This shows that the monochromator resolves the tails better than the grating spectrometer, reducing the $\Delta\lambda_{195\%}$ value by about 0.2 pm. On the other hand, the improved resolution in $\Delta\lambda_{\text{FWHM}}$ for the monochromator should not provide any significant effect on the measured bandwidth in the 0.5pm range. So, slightly higher measured bandwidth in case of the monochromator is probably due to laser bandwidth fluctuations.

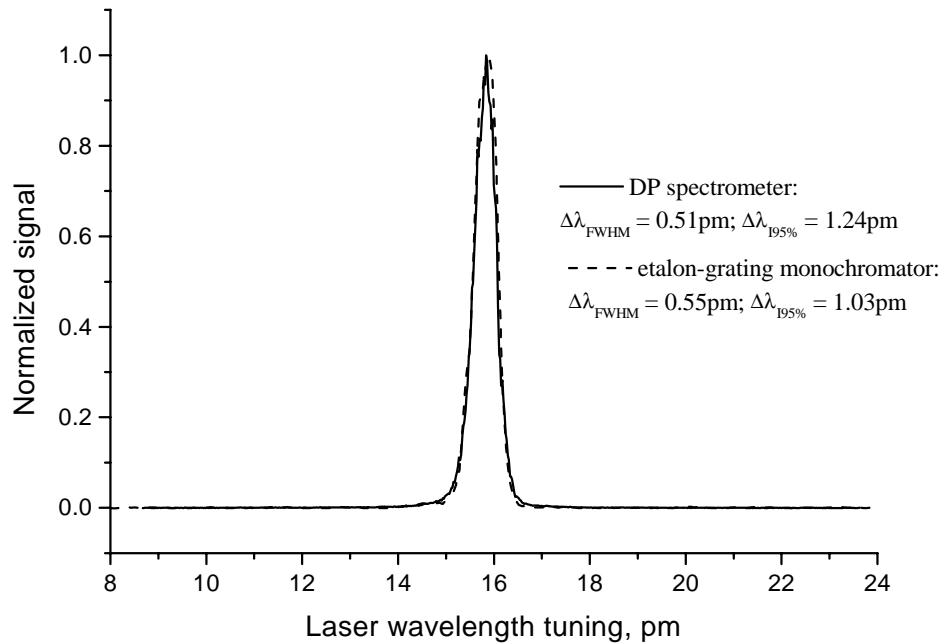


Figure 9. Spectrum of ArF laser measured with a double-pass spectrometer and a high-resolution etalon-grating monochromator.

4. CONCLUSIONS

Two types of new laser spectrum metrology instruments have been discussed: a multi-pass, multi-etalon spectrometer and an etalon-grating monochromator. Both devices provide superior resolution as compared to a typical double-pass grating spectrometer. Each of these instruments requires extremely precise alignment. This requirement may prohibit them from being utilized as a field tool. However, these instruments may successfully be used as a calibration or “gold standard” tool during the manufacturing or testing a laser.

5. REFERENCES

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